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Comparative Analysis of Energy Efficiency in Wheat Production in Different Climate Conditions of Europe

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Abstract: This paper presents results concerning energy efficiency of wheat production considered in the context of specific energy input variation in different climatic conditions of Europe as well as case studies on implementation of selected energy saving measures in practice. The source data collected from the six european union (EU) countries represent five agricultural regions of continental Europe and three climates: continental, temperate and Mediterranean. The life cycle assessment (LCA) methodology was applied to analyze the data excluding of pre-farm gate activities. The total primary energy consumption was decomposed into main energy input streams and it was regressed to yield. In order to compare energy efficiency of wheat production across the geographical areas, the data envelopment analysis (DEA) was applied. It was shown that the highest wheat yield (6.7 t/ha to 8.7 t/ha) at the lowest specific energy input (2.08 GJ/t to 2.56 GJ/t) is unique for temperate climate conditions. The yield in continental and Mediterranean climatic conditions is on average lower by 1.3 t/ha and 2.7 t/ha and energy efficiency lower by 14% and 38%, respectively. The case studies have shown that the energy saving activities in wheat production may be universal for the climatic zones or specific for a given geographical location. It was stated that trade-offs between energy, economic, and environmental effects, which are associated with implementation of a given energy saving measure or a set of measures to a great extent depend on the current energy efficiency status of the farm and opportunity for investment, which varies substantially across Europe.

Key words: Wheat, energy efficiency, trade-off analysis.

1. Introduction

Energy from fossils is an essential input of the modern agricultural production. Even if the sectors of energy and agriculture generate a relatively small part of gross value added (GVA) of national economies (in the EU: 3.1% and 1.7%, respectively), they are crucial in fulfilling demands of growing population for energy and agricultural commodities. According to Smil [1], global cultivated area and energy consumption almost doubled during the 20th century. Further increase of arable land and fossil energy consumption (even if limited) may cause detrimental effects to the environment. Therefore, the intensification of agricultural production must be coupled with conservation efforts and orientated on speeding the agronomic advancements that improve

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crop yield connected with gains to the global carbon market [2]. That is why improvement in energy efficiency of agricultural production is a way to rationalize the use of environment resources. Reduction of energy input implies specific economic and environmental effects. If the trade-off between those effects is positive, it means that energy, economic, and environmental performances are improved simultaneously.

Energy consumption and energy saving potential in a given agricultural production system is differentiated in particular geographical areas. In the EU, the average energy consumption per one hectare of utilized agricultural area (UAA) amounts to 5.9 GJ/ha with a great variation between countries ranging from 3.9 GJ/ha in Portugal to 76.6 GJ/ha in the Netherlands [3]. The significant stream of agricultural energy input is associated with production of wheat (*Triticum* spp.). Energy use for winter wheat production is mainly determined by energy consumption due to fertilizer production and fuel use for tillage operations [4]. Among cereals, wheat is the crop with the largest cultivated area in the EU-27 which accounts for 26 million hectares and 15% share in the total UAA. The average yield of wheat varies from 2 t/ha to 9 t/ha and to a large extent depends on climatic conditions and other biotic and abiotic factors associated with climate such as soil fertility, water availability, and pathogen and weed infestation. According to the Köppen-Geiger climate type map of Europe, the climate zones correspond to continental (Dfb), temperate (Cfb) and Mediterranean (Csa) climates [5]. Although wheat is grown in the three climate environments, the optimal growing conditions and the highest yields are specific for temperate climate environments [6]. However, in relation to the variation of regional climate parameters, the rate of increase in wheat yield displays noticeable deviations from linearity. It suggests that changes in such climate, factors as temperature and precipitation play more determining roles in wheat yield increase in the Southern European countries than in the Northern ones [7-10].

Depending on the climate region, several measures or techniques have been put in practice in order to save energy, decrease greenhouse gas (GHG) emissions and improve the farmer economical return in wheat production. There have been successful cases of increased energy efficiency in situations where crop drying technologies have being improved [11]. The introduction of precision agriculture or precision farming, allowing the reduction of applied nitrogen fertilizer and diesel consumption, has led to energy and economic savings in different conditions [12]. Conservation tillage systems, such as reduced or no-tillage systems, have also been identified as efficient measures to reduce energy input use in agricultural systems. These systems need less fuel and are associated with lower mechanization levels, which reduces production costs and greenhouse gas emissions and its implementation has increased along the years and is recognized as a sustainable and environmental friendly agricultural practice for wheat production in many situations [13].

The objectives of the study were:

(1) To compare energy efficiency of wheat production in Europe with reference to different climate conditions;

(2) To show case studies on implementation of selected energy saving measures and resulting energy, economic, and environmental benefits.

2. Materials and Methods

The source data [11, 14] from the six EU countries was collected in 2011-2012 and represents five agricultural regions of continental Europe: Nordic region (FI, Finland); North-Eastern region (PL, Poland); North-Western region (DE, Germany; NL, Netherlands); South-Eastern region (EL, Greece); and South-Western region (PT, Portugal) [15]. Those five agricultural regions correspond to the three climates: continental regions (FI, PL), temperate (DE, NL), and

Table 1 The primary energy consumption (PEC) equivalents for direct and indirect energy input in wheat production.

Energy input[1]	Unit	PEC	References
Direct			
Electricity	MJ/kWh	9.70	[16]
Diesel	MJ/kg	50.00	[16]
Indirect			
Seeds	MJ/kg	2.61	[16]
Synthetic fertilizers:			
Nitrogen (N)	MJ/kg	48.99	[16]
Phosphorus (P_2O_5)	MJ/kg	15.23	[16]
Potassium (K_2O)	MJ/kg	9.68	[16]
Calcium (CaO)	MJ/kg	1.97	[16]
Magnesium (MgO)	MJ/kg	6.70	[17]
Sulphur (S)	MJ/kg	2.10	[18]
Organic fertilizer	MJ/kg	0.30	[19]
Water	MJ/m^3	0.63	[17]
Pesticides	MJ/kg a.i.	268.4	[16]

The direct energy input associated with human labor and the indirect energy inputs associated with the construction of farm buildings and farm machinery has been excluded because of limited contribution to energy savings in wheat production.

Mediterranean (EL, PT) were the basis for estimation of energy efficiency in wheat production.

The LCA-like approach has been chosen to analyze the data excluding pre-farm gate activities and have thus excluded potential energy consumption associated with supplying of agricultural means, plant breeding, exploitation of water resources, processing into consumer goods, etc.. The level of physical energy inputs was determined using statistical data or in the cases where the data were not available, the estimates based on representative farms were applied. Energy equivalents, which were applied to convert physical data of the input use into the energy data, originated mainly from the BioGrace database [16] (Table 1).

Three scenarios corresponding to wheat production systems with low (L), average (A) and high (H) energy consumption were considered in the countries covered by the study, except the Netherlands, where only a single scenario of average energy input was taken into account (Table 2). Adequately, to those energy input systems, the average yield was estimated.

The primary energy consumption measures of direct energy input, E_D; indirect energy input, E_I; and total energy input, $E_D + E_I$ expressed as specific energy input E_T in GJs per hectare and E_Y in tonne of grains, were estimated. The total energy input was decomposed into main energy input streams and it was regressed to yield. In order to compare energy efficiency of wheat production across the geographical areas, the Data Envelopment Analysis (DEA) was applied [20].

The case studies on energy efficiency in wheat production cover various energy saving measures including the specific ones for wheat production as well as those calculated on a per farm basis (Table 3).

The energy-economic-environmental analysis of case studies was based on a cradle-to-farm-gate LCA model. The GHG emissions were assessed according to the standard ISO 14040 [21]. The cost calculations were based on the economic settings in the study countries, while for the energy use and GHG estimates, whenever possible, common methodologies with the use of energy and emission equivalents were used.

Table 2 Scenarios of energy inputs in wheat production systems by country.

Country	Energy input scenario		
	Low	Average	High
Finland	Direct drilling, low nitrogen input and minimum plant protection	Reduced tillage, conventional nitrogen input and plant protection	Conventional tillage, high nitrogen input and intensive plant protection
Germany	Reduced tillage, low yield and low drying input	Standard values	Conventional tillage, high yields and high drying input
Greece	Low fertilization and no irrigation	Conventional fertilization	Conventional fertilization and irrigation
Netherlands	Wheat production systems do not differ much across the country		
Poland	Low scale production and low yield	Standard values	Intensive production, high yield, high drying energy input and relatively large farms
Portugal	No tillage	Conventional	Conventional with irrigation

Table 3 Case studies—energy saving measures by climate and country.

Climate/Country		Energy saving measures
Temperate:	DE	Two grain drying systems, precision agriculture and reduced fertilizer inputs
	NL	Precision farming, use of compost and less inorganic fertilizer
Continental:	FI	Energy saving in field operations and grain drying (education), optimized use of N-fertilizer and biological N-fixing
	PL	Change in plant rotation, ploughing of straw and application of multi-compound inorganic fertilizer, and application of effective microorganisms
Mediterranean:	EL	Reduced tillage system—minimum tillage considered in production of main crops: cotton and wheat, reduced tillage in wheat and reduced fertilizers and pesticides in cotton through precision farming
	PT	Conventional tillage (reference), no tillage, reduction P_2O_5, and irrigation

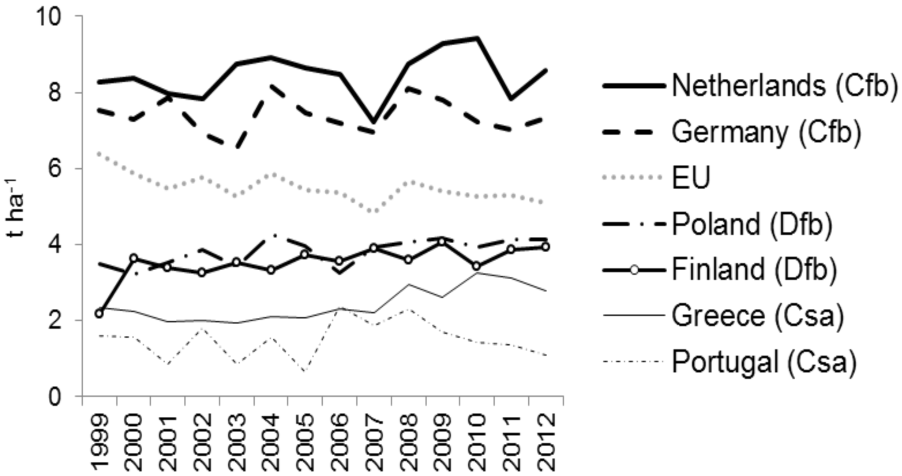

Fig. 1 Wheat yield in the studied countries (climate zone), 1999-2012.

3. Results

The area of wheat production varies greatly in the study-covered countries from 88.3 thousand ha in Portugal to 3213.5 thousand ha in Germany (Eurostat 2008). During the last years, wheat yield fluctuated in a quite stable way across the studied countries although the productivity was distinctly different in the climatic zones: temperate (Cfb), continental (Dfb) and Mediterranean (Csa) (Fig. 1).

In terms of wheat production systems with low, average and high energy input, the highest yield has been recorded for the temperate climate countries (the Netherlands 8.7 t/ha and Germany 6.7 t/ha to 8.3 t/ha), the medium yield level for the continental climate countries (Finland 3.5 t/ha to 6.0 t/ha and Poland 4.8 t/ha to 7.5 t/ha), and the lowest yields were recorded for the Mediterranean climate countries (Greece 2.5 t/ha to 6.0 t/ha and Portugal 3.0 t/ha to 5.0 t/ha) (Table 4). Lower yield values in Mediterranean countries are mainly due to less water availability during the crop cycle, which limits plant growth. The average energy input per hectare of wheat production was highly differentiated in the three climatic zones. In the temperate climate zone, the total energy input across the production systems ranged from 16.2 GJ/ha to 21.3 GJ/ha, in the continental climatic zone from 8.7 GJ/ha to 23.5 GJ/ha, and in the Mediterranean climate region from 2.3 GJ/ha to 6.0 GJ/ha. The specific energy input varied in the ranges of 2.08 GJ/t to 2.56 GJ/t, 2.48 GJ/t to 3.13 GJ/t and 3.01 GJ/t to 4.70 GJ/t for temperate, continental and Mediterranean climatic zones, respectively.

The main specific energy input per tonne of wheat was associated with the use of fertilizers (Table 5). The averages of indirect energy inputs required for the use of fertilizers in the temperate, continental, and Mediterranean climate countries accounted for 1.419, 1.611 and 1.464 GJ/t and share of 59.8%, 59.4% and 49% of the total energy input, respectively.

Table 4 The energy input in wheat production by country and scenario of energy consumption.

Country (area × 1,000 ha)	Energy input Scenario	Average yield t/ha	E_D GJ/ha	E_I GJ/ha	E_T GJ/ha	E_Y GJ/t
Temperate climate countries						
Germany (3213.5)	Low	6.7	4.1	12.1	16.2	2.43
	Average	7.7	6.3	12.3	18.5	2.42
	High	8.3	8.9	12.4	21.3	2.56
Netherlands (156.5)	Average	8.7	6.6	11.6	18.1	2.08
Continental climate countries						
Finland (219.6)	Low	3.5	3.0	5.6	8.7	2.48
	Average	4.5	3.9	8.0	12.0	2.66
	High	6.0	5.7	9.9	15.7	2.61
Poland (2278.0)	Low	4.8	3.9	9.6	13.5	2.81
	Average	5.8	4.1	10.9	15.1	2.60
	High	7.5	7.9	15.5	23.5	3.13
Mediterranean climate countries						
Greece (657.1)	Low	2.5	5.3	6.5	11.8	4.70
	Average	5.0	10.0	9.9	19.9	3.99
	High	6.0	12.8	9.9	22.7	3.78
Portugal (88.3)	Low	3.0	1.6	7.4	9.0	3.01
	Average	3.0	5.7	7.2	12.9	4.29
	High	5.0	6.3	10.7	17.0	3.39

Table 5 Specific energy input in GJ/t and percentage share by sources and climate zones of Europe.

Climate Statistics	Energy input				
	Seeds	Fertilizers	Pesticides	Diesel use	Drying
Temperate climate countries					
Min-Max	0.043-0.069	1.179-1.680	0.074-0.122	0.414-0.676	0.053-0.654
Mean ± SE	0.054 ± 0.006	1.419 ± 0.105	0.092 ± 0.011	0.501 ± 0.060	0.306 ± 0.136
%	2.3	59.8	3.9	21.1	12.9
Continental climate countries					
Min-Max	0.087-0.160	1.332-1.902	0.080-0.121	0.363-0.812	0.000-0.505
Mean ± SE	0.122 ± 0.011	1.611 ± 0.092	0.101 ± 0.008	0.555 ± 0.076	0.326 ± 0.103
%	4.5	59.4	3.7	20.5	12.0
Mediterranean climate countries					irrigation
Min-Max	0.074-0.148	1.464-2.264	0.080-0.214	0.533-2.120	0.000-0.458
Mean ± SE	0.116 ± 0.012	1.892 ± 0.130	0.144 ± 0.021	1.581 ± 0.243	0.127 ± 0.083
%	3.0	49.0	3.7	41.0	3.3

The diesel use for field operations was the second main energy input. The relatively high amount of diesel used was recorded for the Mediterranean climate countries (1.581 GJ/t) and this figure was 2.8 times and 3.2 times higher than those of the temperate and continental climate countries. The other significant direct and indirect energy inputs have been to a great extent specific for geographical location and climatic zones. In the temperate and continental climate regions, the additional energy on wheat production has been associated with drying while in the Mediterranean climate region with irrigation.

There is a general linear tendency for higher energy use to be associated with higher yield (Fig. 3 and Table 5). The three fitted lines of regression between the total energy input and yield correspond to the three climate zones of Europe. The parallelism of lines indicates that the average increase in yield per unit increase of energy input was similar across climatic zones and accounted for 0.27 t/GJ. The yield difference between the lines is 1.3 t/ha between temperate and continental climatic zones and 1.4 t/ha between continental and Mediterranean climatic zones. The results of DEA analysis of energy efficiency in wheat production for the three climatic zones of Europe are presented in Table 6.

In comparison with the most efficient energy use in temperate region countries (NL, DE), the energy efficiency of wheat production in continental and Mediterranean region countries was on average lower by 14%, and 38%, respectively. It is worth noticing that the ranges of energy efficiencies between climatic zones resulted from low, average and high energy input systems in a given climate overlapped each other.

Different examples of energy saving measures were applied in case studies reported by six countries covered by the study (Table 7). In general, they enable improvement in energy efficiency of wheat production or show the potential of trade-offs between energy savings, GHG-emissions and farm economics. The exemplified energy saving measures reflects the activities which may be considered as universal (like precision agriculture, reduced tillage and fertilizer use) or specific (like optimization of drying process or implementation of irrigation system) for a given geographical location.

Indifferent of the climatic zone, all the presented energy efficiency measures targeted the main direct and indirect energy inputs in wheat production. Energy efficiency measures considered in the temperate climate countries (DE, NL) assumed reduction of electricity/fuel use in drying and reduction of mineral fertilization by precision farming (also a potential for reduction of direct energy use), reduced application of nitrogen and organic soil improver. In

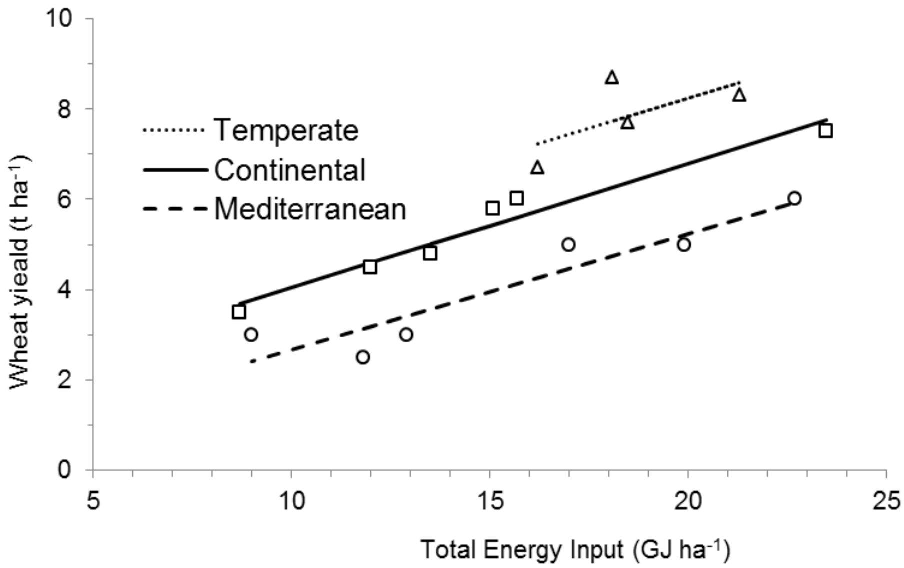

Fig. 3 The regression between total energy input and yield by climatic zones of Europe.

Table 6 The parameters of regression between total energy input and wheat yield and estimates of relative energy efficiency by climatic zones.

Climatic zones of Europe	Regression analysis parameters			DEA analysis
	Intercept	Regression coefficient	R^2	Relative energy efficiency (range)
Temperate	2.880	0.268	0.412	1.00 (0.81-1.00)
Continental	1.307	0.274	0.956	0.86 (0.66-0.86)
Mediterranean	0.094	0.266	0.878	0.62 (0.44-0.69)

Table 7 Energy efficiency measures and associated reduction effects of cost, energy use and GHG emission by country case studies.

Energy efficiency measure	Annualized cost		Primary energy use		GHG emission	
	€/ha	%	MJ/ha	%	CO_2e/ha	%
Germany (per crop basis)						
Dryer I (energy use optimization)	20	2.1	801	4.2	43	2.5
Dryer II (energy use optimization)	13	1.4	440	2.3	23	1.3
Precision farming	31	3.3	640	3.3	61	3.5
Reduced nitrogen use	0	0.0	846	4.4	101	5.9
Netherlands (per crop basis)						
Precision farming	24	0.4	810	2.9	30	1.0
Compost application	-12	-0.2	1,837	6.6	136	4.5
Finland (medium energy intensity)(1)						
Thermal insulation of dryer	5.0	-	164	1.3	20	-
Fuel economic tractor operating (educ.)	4.5	-	145	1.2	17	-
Poland (per crop basis)						
Change in plant rotation	20	1.8	836	5.5	49	3.1
Straw ploughing plus multi-fertilizer	157	13.8	0	0.0	0	0.0
Effective microorganisms	11	1.0	218	1.4	44	2.8
Greece (per farm or per crop basis)						
Reduced tillage in wheat and cotton	1,050	23.4	76,531	8.5	5,581	7.7
Reduced tillage in wheat	650	14.7	21,861	2.4	1,594	2.2
Precision farming	18	0.2	59,377	6.6	6,191	8.5
Portugal (per crop basis)						
No tillage	46	8	3,062	45	104	30
Reduced use of phosphorus	6	2	126	3	9	2
Irrigation(2)	-242	7	-6,808	3	-364	15

(1) Data were reported per t basis and recalculated using average yield 4.5 t/ha [14].

(2) Negative figures for cost, energy use and GHG emission are associated with implementation of the irrigation system; the percentages are associated with positive effects due to increased yield.

the continental climate countries (FI, PL), the measures assumed reduction of direct energy use by insulation of dryers, efficient diesel use in field operation and application of multi-fertilizers while reduction of indirect energy use by lower fertilizer use by changes in crop rotation (including presence of leguminous crops), ploughing of straw and application of effective microorganisms. The implementation of energy saving activities in wheat production may be particularly efficient in Mediterranean climate countries (EL, PT). The reduction of direct energy inputs was associated with no-tillage or reduced tillage and implementation of irrigation systems as well as with reduction of indirect energy use by precision agriculture and limited phosphorus use.

4. Conclusions

The energy input in wheat production is highly differentiated across the climatic zones of Europe. The highest wheat yields (6.7 t/ha to 8.7 t/ha) at the lowest specific energy input (2.08 GJ/t to 2.56 GJ/t) are unique for temperate climate conditions. On average, the yield in continental and Mediterranean climatic conditions is lower than that of temperate climate conditions by 1.3 t/ha and 2.7 t/ha, respectively. Across the climatic zones, there is a similar linear tendency for higher wheat yield to be associated with the higher energy input. On average, the wheat yield increases by 0.27 t/ha per 1 GJ of energy input. The indirect energy embodied in fertilizers followed by direct energy in fuels is the main energy input in wheat production. In comparison with the most efficient energy use in temperate climate conditions, the energy efficiency in the continental and Mediterranean regions is lower by 14% and 38%, respectively.

The case studies associated with implementation of energy efficiency measures show that there is a potential for energy savings in wheat production and trade-off effects between energy savings, GHG-emissions, and farm economics. The exemplified energy saving measures reflects the energy saving activities which may be universal for Europe or specific for a given geographical location. The profitability associated with implementation of a given energy saving measure or a set of measures to depend a great extent on the current status of the farm and opportunity for investment, which varies substantially across Europe.

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